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Enhancing Quality and Safety of Central Venous Catheter Insertion using Projection Mapping: A Prospective Observational Simulation Study with Eye-tracking Glasses

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Enhancing Quality and Safety of Central Venous Catheter Insertion using Projection Mapping: A Prospective Observational Simulation Study with Eye-tracking Glasses

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Keywords: Central venous catheter insertion; Eye-tracking analysis; Medical simulation; Projection mapping; Realtime ultrasound guidance

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Abstract

Objectives

We aimed to evaluate the effect of projection mapping (PM) on the quality and safety of central venous catheter (CVC) insertion under real-time ultrasound guidance.

Design

Prospective, observational, simulation study

Setting

Anaesthesiology and Critical Care, Yokohama City University Medical Center, Yokohama, Japan

Participants and Methods

Twelve rotating residents (post-graduation year [PGY] 1 and 2) and 8 anaesthesia residents (PGY 3–5) placed the CVC in the internal jugular vein in a simulator under the real-time ultrasound guidance using the short-axis out-of-plane approach. The ultrasound image was provided either just caudad to the puncture site using the PM method or on the monitor of the ultrasound machine (conventional method) placed next to the simulator's right shoulder. Each resident performed four punctures alternating between the PM and conventional methods, and the first method for each resident was chosen randomly. Eye-tracking analysis was also used to evaluate differences in gaze

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behaviour.

Primary and Secondary Outcome Measures

The primary outcome was the procedure time defined as the time from the application of the ultrasound probe on the puncture field until successful puncture of the vein. The secondary outcomes were incidence of complications and eye-tracking analysis data.

Results

The time to complete the line placement was significantly shorter for the PM than for the conventional method [median (interquartile range) 22.5 (15.5–30.6) s vs 30.0 (20.4–95.4) s; p=0.02, Wilcoxon's singed rank test]. The incidence of posterior vessel wall puncture was significantly lower in the PM method (0% vs 25%; p=0.02, McNemar's test). Eye-tracking analysis revealed that the percentage of time spent gazing at the ultrasound image was higher in the PM than in the conventional method (61.6 [55.0–69.2]% vs. 45.7 [34.1–54.5]%; p<0.01).

Conclusions

The PM method facilitates ultrasound-guided CVC placement while preventing excessive needle advancement in the inexperienced operators. This was accompanied by enhanced fixation of the participants' line-of-sight on the ultrasound image.

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Strengths and limitations of this study

- This study showed that modern projection mapping technology improves the quality and safety of central venous puncture, especially for novices.
- By reducing eye and head movement during the operation, central venous puncture can be performed more quickly and with fewer complications.
- This study used eye tracking data to show how the operator's gaze shifts during central venous puncture and theorised why improvements in quality and safety occur.
- This study was conducted in a simulated environment, which did not fully replicate the real-world situation.
- The basic settings for ere-tracking analysis vary, and the most suitable settings for central venous puncture are not obvious, so whether the settings used in this study are optimal is unclear.

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INTRODUCTION

Real-time ultrasound guidance has become the standard practice for the central venous catheter (CVC) placement in the internal jugular vein. [1–9] In this procedure, the short-axis out-of-plane approach is more common than the long-axis in-plane approach. [10–14] For the short-axis out-of-plane approach, the operator slides the ultrasound probe in the caudad direction while advancing the puncture needle so that the needle tip is always located. This requires a certain level of skill, and some investigators have raised a concern that the risk of excessively deep needle advancement may be higher than that in the conventional landmark methods, especially in the hands of inexperienced operators. [15–17] This risk may lead to posterior vessel wall puncture, and serious complications such as vertebral artery puncture and pneumothorax may ensue. [18–24] During the real-time ultrasound-guided method, the operator must alternately observe the ultrasound image and the puncture site which are located apart. Shifting the line-of-sight may increase the workload and interfere with the hand-eye coordination, especially for the inexperienced operators. Indeed, recent studies on aviation safety and automobile driving have shown that head-up displays, which present necessary information within the line-of-sight, allowed for more precise manoeuvring to keep flight paths and driving lanes by reducing the shift of the line-of-sight. [25–27] They also

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reported that the reduction in driver's line-of-sight shift increased the time spent gazing at the signals and obstacles. Similarly, the use of wearable glasses that display the UI makes the ultrasound-guided radial artery puncture procedure in children faster and more successful than the conventional method. [28,29]

Recently, advances have been made in projection mapping (PM) technology, which can project precise images onto surfaces. [30] Using this technique, ultrasound images can be projected near the site where the CVC is placed. We hypothesised that projecting ultrasound images near the puncture site would improve the speed and safety of CVC placement performed by inexperienced operators by reducing their line-of-sight shift. Recently, high-performance eye-tracking system is available for medical research, and an eye-tracking analysis of gaze patterns during CVC insertion was reported. [31] In the present study, we used eye-tracking technology to analyse resident's gazes during the CVC insertion to evaluate the impact of PM on the operator's gaze behaviour.

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METHODS

This prospective observational study was conducted at the Yokohama City University Medical Center (Yokohama, Japan). This study was approved by the Institutional Review Board of Yokohama City University Medical Center (B200900073), and written informed consent was obtained from all participants. Volunteer residents were enrolled over 12 months from January to December 2023. The Japanese residency system provides basic training in all fields of clinical medicine during the first 2 years after graduation, followed by 5 years of specialised training for anaesthesia residents. Residents up to 2 years post-graduation (rotating residents post-graduate year: R-PGY 1–2) and anaesthesia residents 3–5 years post-graduation (AR-PGY 3–5) participated in this study.

Patient and public involvement

Patients and/or the public were not involved in the design, conduct, reporting, or dissemination plans of this research.

Study protocol

All participants attended a one-hour training course on real-time ultrasound-guided

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central venous catheterisation prior to the study. This training course included a lecture on ultrasound-guided puncture and hands-on training using the simulator (CVC Puncture Insertion Simulator Ⅱ; Kyoto Kagaku Co. Ltd., Kyoto, Japan) under the supervising physician. Participants were given time to familiarise themselves with an ultrasound machine (EDGE; Sonosite, Inc., Bothell, WA, USA) and received instructions on how to operate them. A 35 mm metal needle was used for puncture (Argyle™ Fukuroi SMAC™ Plus Micro Needle Type). Before the puncture, participants wore a head-mounted eye-tracking system (Tobii Pro Glasses 2; Tobii, Karlsrovagen, Sweden). Their eyes were calibrated using the eye-tracking software (Tobii Pro Lab, Version 1.130) by having the participant following on a black dot of the small white square card across different areas. After the calibration, participants wore surgical gloves and performed the procedures using the short-axis out-of-plane approach. Figure 1 shows the simulation setup. The participant stood at the simulator's head and the ultrasound machine was placed next to the simulator's right shoulder so that the participant, puncture site, and ultrasound machine were as much on the straight line as possible. During the conventional method, the participant performed the puncture by looking at the screen of the ultrasound machine.

In the PM method, the ultrasound image was projected from the upper right side of the

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participant onto the flattened drape just caudal to the puncture site by connecting an ultrasound machine to a projector (Light Scene EV-110, Seiko Epson Corporation, Nagano, Japan) (Fig. 2). When viewing the PM image, the ultrasound machine screen was masked and the participant was not able see it.

Participants wore the eye-tracking device and performed a total of four punctures, alternating between using PM (PM method) and ultrasound machine screen (conventional method). Participants were randomly assigned to start with PM method or conventional method.

Measurements

The resident's performance was recorded from two directions to allow detailed analysis of the puncture, and the researcher also made thorough observations. ultrasound images were also recorded for analysis. The following outcomes were measured for each method. The primary outcome was the procedure time defined as the time from the application of the ultrasound probe on the puncture field until successful puncture of the vein that was confirmed by withdrawing 1 mL of water in the simulator's jugular vein. The secondary outcomes were as follows. The task success rate was defined as the number of punctures completed within 10 min from the application of the ultrasound probe to the

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placement of the guidewire over the total number of punctures for each method (i.e., 2 punctures × 20 residents = 40 punctures for each method). The incidence of arterial and posterior vessel wall puncture was determined by reviewing the recorded ultrasound images by the two blinded researchers. If the needle tip was not fully determined, the needle's depth and the movement of the posterior vessel wall on the ultrasound image were taken as signs of the posterior vessel wall puncture. The first-pass success was defined as the successful puncture of the jugular vein on the first attempt without redirecting the needle, and the first-pass success rate was recorded. The number of needle re-directions was defined as changes in the direction of needle regardless of whether the needle is removed from the skin or not.

A previous study of the eye-tracking analysis during ultrasound-guided CVC placement revealed that the two most relevant areas of interest (AOIs) included the ultrasound image and the puncture site with its surrounding area. [31] We named these two areas as AOI-UI (ultrasound image) and AOI-PS (puncture site) respectively (Fig. 3) and recorded the time each participant's line-of-sight stayed within these AOIs.

The eye-tracking data were further analysed for the following items:

(i) The fixation-time-image rate (%): Fixation is defined as the gaze fixes at a point in the AOI for over 60 ms. The fixation-time-image rate is the percentage of fixation time within

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the AOI-UI over the total fixation-time (fixation-time in AOI-UI + fixation-time in AOI-PS) during the puncture. The fixation-time-image rate indicates how focused the participant was on the ultrasound image compared to the puncture site. (ii) Total-fixation-Image/Total-Dwell-Image (%): Dwell-time is the total time during which the participant's gaze was recorded inside the AOI. The dwell time includes the time taken to move the line-of-sight as well as the fixation time. This item is the percentage of the fixation time over the dwell time in the AOI-UI and indicates how focused the participant is on the specific target within the ultrasound image (Fig. 4).

Calculation of the sample size

Based on the study by Ball et al, a two-tailed Wilcoxon signed-rank test power analysis was conducted based on the primary endpoint of the study, which was the procedure time defined above. [14] Considering the data from the pilot study at our own facility, to possess a power of 80% to avoid type-II error with significance at the 0.05 level, a sample size of 20 residents would be needed to detect a 50% difference for the procedure time between the PM method and conventional method, using R package 'pwrss' (Bulus, M. [2023]. pwrss: Statistical Power and Sample Size Calculation Tools. R package version 0.3.1. https://CRAN.R-project.org/package=pwrss). In addition, we estimated 10 to 20%

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of missing values or measurement errors.

Statistical analysis

Wilcoxon signed-rank tests were used for nonparametric paired samples (the procedure time, the number of needle re-directions, the fixation-time-image rate, and the Total-fixation-Image/Total-Dwell-Image) and exact McNemar's tests were used to compare the task success rate, first-pass success rate, and the incidence of artery and posterior vessel wall puncture. Additionally, the univariate correlation between the procedure time and puncture experience was assessed using Spearman's rank correlation. The level of significance was set at $p<0.05$. All analyses were performed using IBM SPSS Statistics, Version 29.0.2.0 (Armonk, NY, USA).

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RESULTS

Twenty-two residents, each having less than 50 CVC puncture experiences, were recruited and participated in the study, but 2 dropped out owing to incomplete eye-tracking data. Therefore, the data of 20 residents were subject to final analysis. Less experienced trainees (R-PGY 1–2) comprised 60% of the participants (12/20), including 5 residents with no prior CVC puncture experience on actual patients (Table 1).

The procedure time was significantly shorter in the PM method than in the conventional method (median [interquartile range]: 22.5 [15.5–30.6] s vs 30.0 [20.4–95.4] s; p=0.02) (Fig. 4-a). The success rate was 100% in both methods, and no arterial puncture occurred in either. Posterior vessel wall punctures occurred in 5 of 20 participants in the conventional method, but not in the PM method (0% vs. 25%; p=0.02). No significant differences were observed in the first-pass-success rate (62.5% vs. 52.5%; p=0.45) and the number of needle re-directions (1.5 [1.0–1.9] vs 1.5 [1.0–2.4]; p=0.26). No significant correlation existed between the procedure time and puncture experience (PM method, r=0.07, p=0.78; conventional method, r=0.13, p=0.58). The fixation-time-image rate was significantly higher in the PM method (61.6 [55.0–69.2]% vs. 45.7 [34.1–54.5]%; p<0.01) (Fig. 4-b). Total-fixation-Image/Total-Dwell-Image was significantly higher in the PM method (92.7 [89.6–94.5]% vs 87.8 [73.5–93.7]%; p=0.01) (Fig. 4-c). Two researchers reviewed the eye-tracking video images and confirmed that, in all participants, the puncture site was constantly captured within the AOI-UI during the PM methods but not during the conventional method.

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DISCUSSION

The results of this study demonstrated that the PM method allows residents to perform CVC punctures faster and with lower incidence of posterior vessel wall puncture compared with the conventional method. These findings indicate that the PM method facilitates the identification of the needle tip by the ultrasound and improves the hand-eye coordination required for the CVC puncture. This would contribute to safer puncture in the real clinical settings.

In contrast, no differences were observed between the two methods in terms of the overall and the first-pass success rates, incidence of arterial puncture, and number of needle redirection. Our results of the 100% overall success rate with no arterial puncture suggest that our simulator is too easy to elucidate any possible difference between the two methods (*i.e.*, ceiling effect). The first-pass success using the short-axis out-of-plane approach requires determination of the adequate puncture site as well as the right direction of the needle. The ultrasound plays a role in the former by identifying the position of the jugular vein, but not in the latter because the needle is visualised only after it is advanced into the tissue, i.e., after the needle direction has been determined. This limited role of ultrasound may account for the lack of difference in the first-pass success rate between the two methods. Additionally, participants were possibly familiar with the simulator due to the training conducted immediately before.

The eye-tracking data revealed that, compared to the conventional method, the PM method was associated with longer fixation in the ultrasound image relative to the puncture site. Moreover, when the line-of-sight was within the ultrasound image, the PM method promoted fixation on the key structure more than the conventional method. Longer fixation indicates that the operator focused longer on the region of interest. Therefore, our results suggest that, compared to the conventional method, the PM method helps our participants to focus more on the ultrasound image than the puncture site as well as on the key structure within the ultrasound image. These characteristics are similar to those of the skilled operators demonstrated by previous studies of vessel punctures and nerve blocks and may account for shorter procedure time and lower incidence of posterior vessel wall puncture demonstrated in this study. [32,33]

Two mechanisms may account for our results of the eye-tracking analysis. First, the shorter distance between the ultrasound image and the puncture site with the PM method reduced the workload associated with the shift of the line-of-sight. Second, with the PM method, the puncture site was always captured within the AOI-UI. In healthy people, the horizontal viewing angle is about 200° and the vertical is 130°. [34] The viewing angle of the eye-tracking camera is 82° and 52° respectively; therefore, what was visible in the eye-tracking video image was likely to be in the participants' field of view as well. Therefore, it is likely that the PM method allowed our participants to receive some information about the direction and depth of the needle from their peripheral field of view even when their line-of-sight was on the ultrasound image, allowing more fixation on the ultrasound image and also on the key structure within it. [35] In contrast, in the conventional method, the ultrasound image and the puncture site were far apart, and the operator had to consciously move the line-of-sight between the two sites, which o fixation.

This study had some limitations. Firstly, the study was conducted in a simulated environment, which did not fully replicate the real-world situation. Further studies on the efficacy of PM on actual patients are warranted. Secondly, the definition of fixation may differ according to what one sees, and there is no evidence for ultrasound-guided procedures. We defined fixation as 60 ms or longer in this study based on the previous study for reading and observing objects, but the average fixation for the scene perception is reported to be 220 ms to 360 ms. [36,37] Thirdly, all our participants had less than 50 CVC placement experiences and were considered novices according to previous studies. [22] It has been demonstrated that the gaze pattern during the CVC placement differ between experienced and inexperienced operators; therefore, our results may not be applicable to those with more experiences with the CVC placement. [31]

In summary, our results suggests that the presentation of ultrasound images close to the puncture field by our PM device facilitates the safe real-time ultrasound-guided CVC puncture by novice operators. The finding has the potential to be applied to various other ultrasound-guided procedures. With future technological advances, such as the miniaturisation of projectors, this method will evolve for daily use.

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Competing Interests The authors declare that they have no conflicts of interest.

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Contributions AM and AF are joint first authors. AM, AF, Kyota N, TA, KT and HS conceptualised the study. AM, AF, HS, DK, KM, and HS designed the study and collected data. AM, AF, TA and HS were involved in analysis of the data. AM, AF, HS drafted the manuscript. HK, Kazue N, and TG revised the manuscript. All authors contributed to data interpretation, reviewed the successive drafts and approved the final version of the manuscript.

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Patient consent for publication Not applicable.

Ethics approval This study was approved by the Institutional Review Board of Yokohama City University Medical Center (B200900073)

Data availability statement Data are available upon reasonable request. The data underlying this article will be shared on reasonable request to the corresponding author.

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Table 1 Demographic variables of participating residents.

Participant characteristic variables	**n = 20 (%)**
Clinical year	
R-PGY 1	2 (10)
R-PGY 2	10 (59)
AR-PGY 3	5 (25)
AR-PGY 4	2 (10)
AR-PGY 5	1 (5)
Prior experience of CVC insertions (times)	
<10	12 (60)
11–20	5 (25)
21–30	1 (10)
31–40	1 (10)
41–50	1 (10)

AR, anaesthesia resident; CVC, central venous catheter; PGY, post-graduate year; R, resident

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Figure legends

Fig 1. Setting of the simulation.

The simulator was placed on the operating table. The ultrasound machine was placed next to the simulator's right shoulder and projector behind the participant. CVC, central venous catheter

Fig 2. Projection mapping setup

The projector was used to project the ultrasound image from the upper right of the participant, very close to the puncture site. The images of the projection mapping are highly accurate and comparable to the ultrasound machine screen in CVC puncture. CVC, central venous catheter

Fig 3. Eye-tracking analysis

Left panel: Analysis of PM Method

Set AOI to puncture site and ultrasound image (projection mapping)

Right panel: Analysis of conventional method

Set AOI to puncture site and ultrasound image (ultrasound machine screen)

AOI, area of interest; AOI-UI, AOI-ultrasound image; AOI-PS, AOI-puncture site

Fig 4. Formula for fixation-time-image rate and dwell-time rate

AOI, area of interest; AOI-UI, AOI-ultrasound image; AOI-PS AOI-puncture site

Fig 5.

a: The procedure time was significantly shorter in the PM method ($p=0.02$).

b: The Fixation-time rate was significantly higher in the PM method ($p<0.01$).

c: Total-fixation-Image/Total-Dwell-Image was significantly higher in the PM method ($p=0.01$)

PM, projection mapping

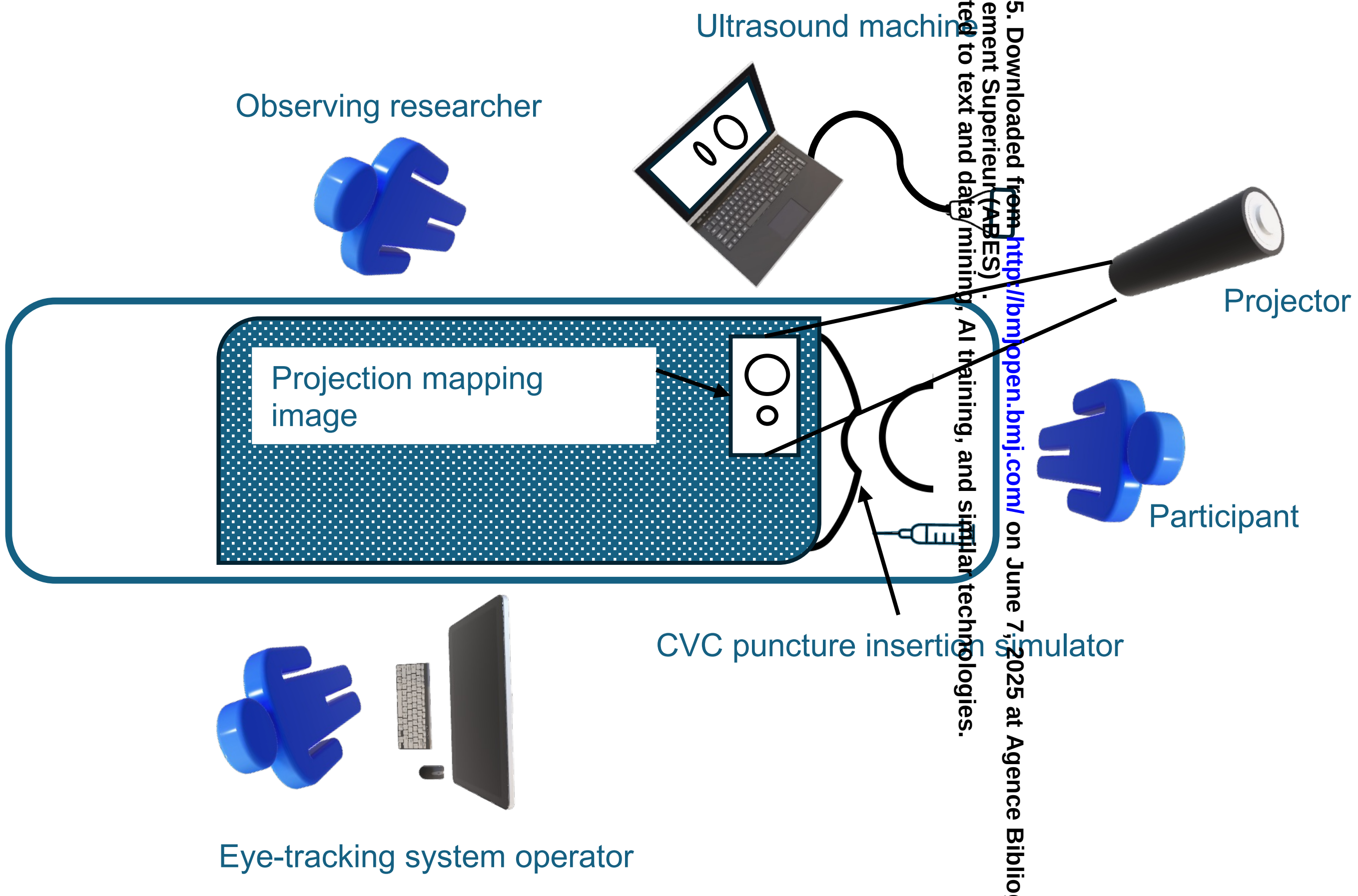
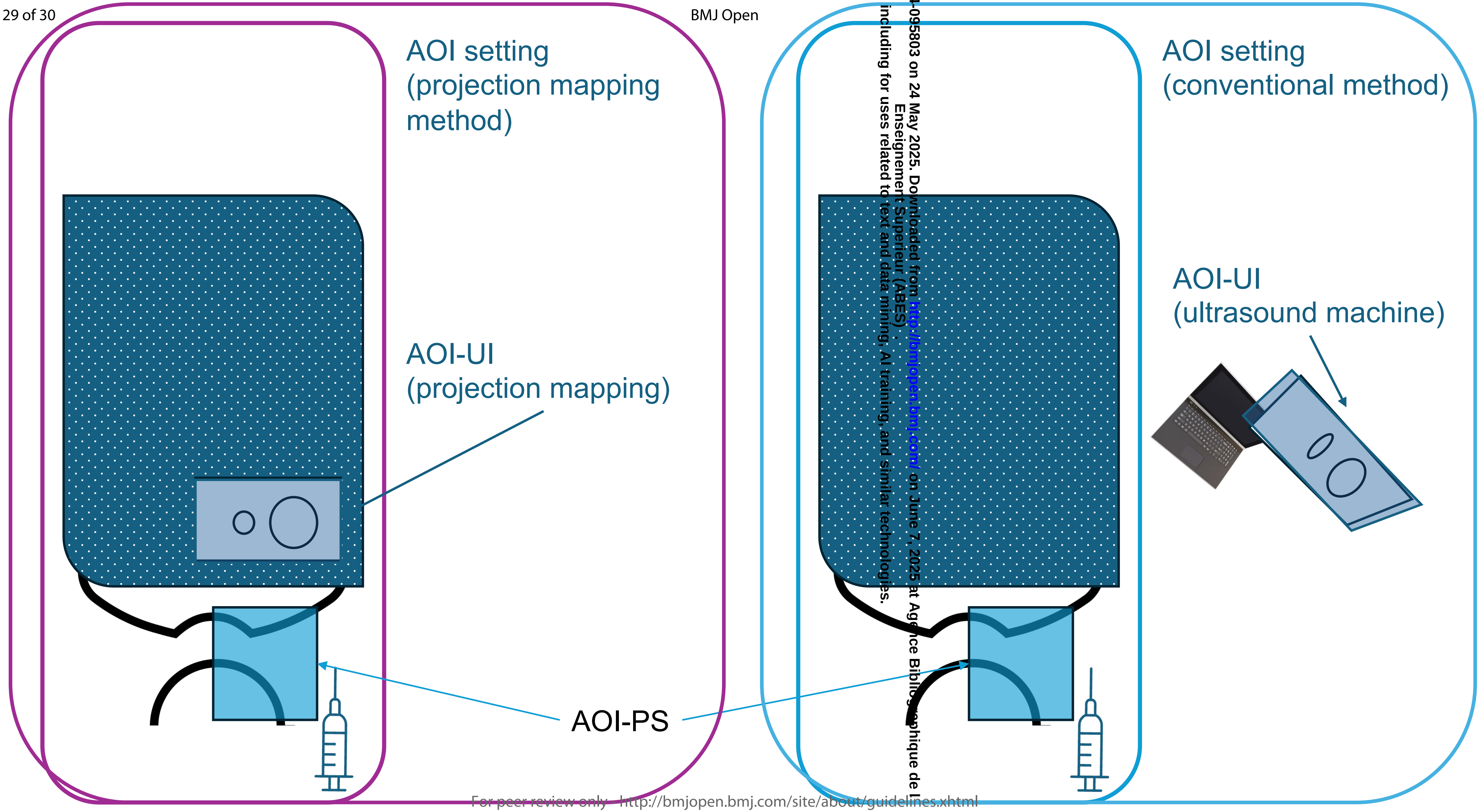

Ultrasound machine
Observing researcher
Projector
Projection mapping image
Participant
CVC puncture insertion simulator
Eye-tracking system operator

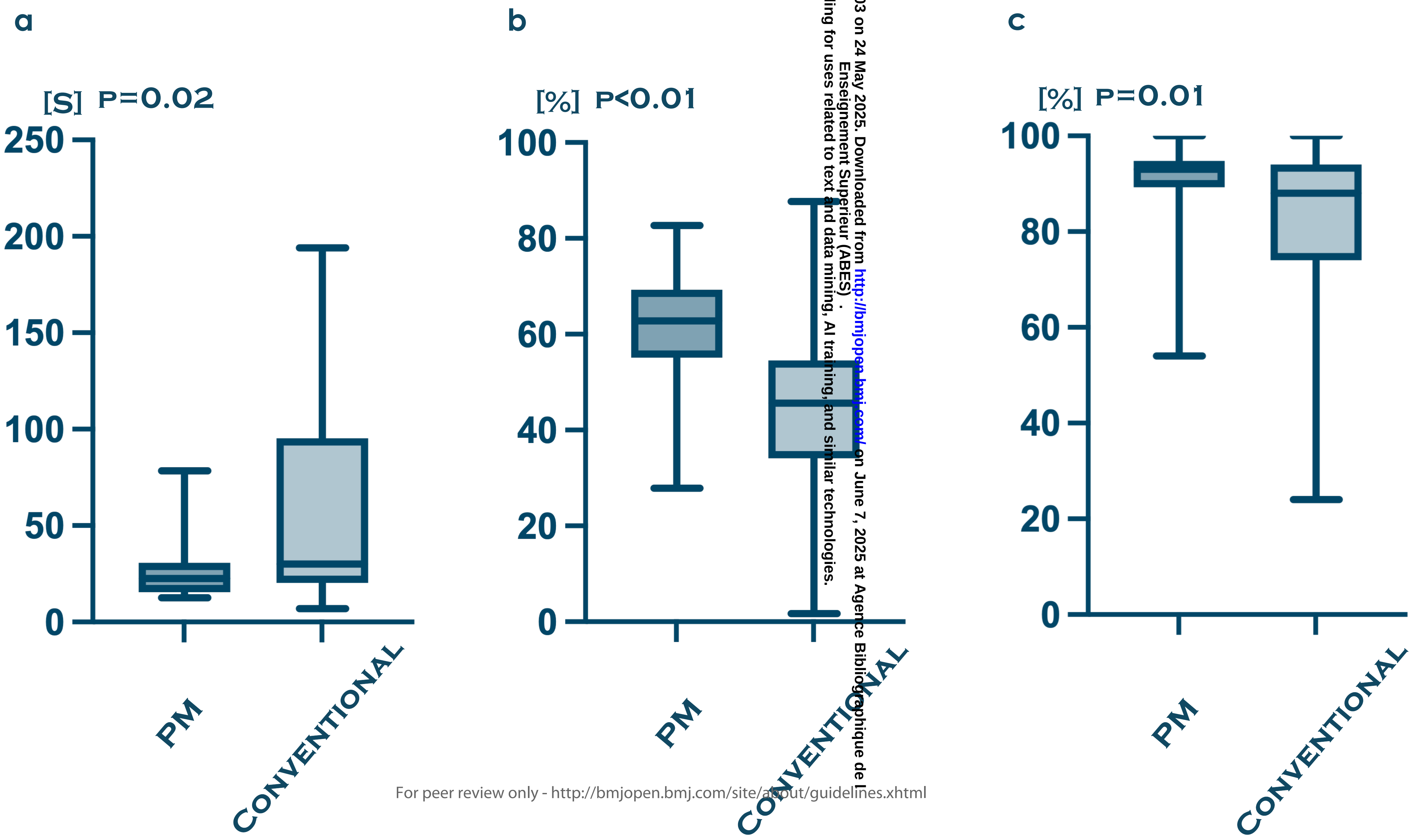
Fig 2. Projection mapping setup
The projector was used to project the ultrasound image from the upper right of the participant, very close to the puncture site. The images of the projection mapping are highly accurate and comparable to the ultrasound machine screen in CVC puncture. CVC, central venous catheter

201x151mm (300 x 300 DPI)


AOI setting
(projection mapping
method)
AOI-UI
(projection mapping)
AOI-PS
AOI setting
(conventional method)
AOI-UI
(ultrasound machine)

$$\text{Fixation-time-image rate (\%)} = \frac{\text{Fixation-time AOI-UI}}{\text{Fixation-time AOI-UI} + \text{Fixation-time AOI-PS}} \times 100$$

$$\text{Dwell-time-image rate (\%)} = \frac{\text{Dwell-time AOI-UI}}{\text{Dwell-time AOI-UI} + \text{Dwell-time AOI-PS}} \times 100$$


a
[S] P=0.02
250
200
150
100
50
0
PM
CONVENTIONAL
b
[%] P<0.01
100
80
60
40
20
0
PM
CONVENTIONAL
c
[%] P=0.01
100
80
60
40
20
0
PM
CONVENTIONAL

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Enhancing quality and safety of central venous catheter insertion using projection mapping: A prospective observational simulation study with eye-tracking glasses

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Enhancing quality and safety of central venous catheter insertion using projection mapping: A prospective observational simulation study with eye-tracking glasses

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Keywords: Central venous catheter insertion; Eye-tracking analysis; Medical simulation; Projection mapping; Realtime ultrasound guidance

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ABSARACT

Objectives

We aimed to evaluate the effect of projection mapping (PM) on the quality and safety of central venous catheter (CVC) insertion under real-time ultrasound guidance.

Design

Prospective, observational, simulation study

Setting

This study was conducted at the Yokohama City University Medical Center (Yokohama, Japan). Volunteer residents were enrolled over 12 months from January to December 2023.

Participants and methods

Twelve rotating residents (post-graduation year [PGY] 1 and 2) and eight anaesthesia residents (PGY 3–5) placed the CVC in the internal jugular vein in a simulator under the real-time ultrasound guidance using the short-axis out-of-plane approach. The ultrasound image was provided either just caudad to the puncture site using the PM method or on the monitor of the ultrasound machine (conventional method) placed next to the simulator's right shoulder. Each resident performed four punctures alternating between the PM and conventional methods, and the first method for each resident was

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chosen randomly. Eye-tracking analysis was also used to evaluate differences in gaze behaviour.

Primary and secondary outcome measures

The primary outcome was the procedure time defined as the time from the application of the ultrasound probe on the puncture field until successful puncture of the vein. The secondary outcomes were incidence of complications and eye-tracking analysis data.

Results

The time to complete the line placement was significantly shorter for the PM than for the conventional method [median (interquartile range) 22.5 (15.5–30.6) s vs 30.0 (20.4–95.4) s; p=0.02, Wilcoxon's singed-rank test]. The incidence of posterior vessel wall puncture was significantly lower in the PM method (0% vs 25%; p=0.02, McNemar's test). Eye-tracking analysis revealed that the percentage of time spent gazing at the ultrasound image was higher in the PM than in the conventional method (61.6 [55.0–69.2]% vs. 45.7 [34.1–54.5]%; p<0.01).

Conclusions

The PM method facilitates ultrasound-guided CVC placement while preventing excessive needle advancement in the inexperienced operators. This was accompanied by enhanced fixation of the participants' line-of-sight on the ultrasound image.

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Strengths and limitations of this study

- This study used eye-tracking to show how the operator's gaze shifts during central venous puncture.
- Novices with limited and relatively uniform experience of CVC placement participated in the study.
- This study was conducted in a simulated environment, which did not fully replicate the real-world situation.
- The basic settings for ere-tracking analysis vary, and the most suitable settings for central venous puncture remain unclear.

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INTRODUCTION

Real-time ultrasound guidance has become the standard practice for the central venous catheter (CVC) placement in the internal jugular vein. [1–9] In this procedure, the short-axis out-of-plane approach is more common than the long-axis in-plane approach. [10–14] For the short-axis out-of-plane approach, the operator slides the ultrasound probe in the caudad direction while advancing the puncture needle so that the needle tip is always located. This requires a certain level of skill, and some investigators have raised a concern that the risk of excessively deep needle advancement may be higher than that in the conventional landmark methods, especially in the hands of inexperienced operators. [15–17] This risk may lead to posterior vessel wall puncture, and serious complications such as vertebral artery puncture and pneumothorax may ensue. [18–24] In the real-time ultrasound-guided method, the operator must alternately observe the ultrasound image and the puncture site, which are located separately. Shifting the line-of-sight may increase the workload and interfere with the hand-eye coordination, especially for the inexperienced operators. Indeed, recent studies on aviation safety and automobile driving have shown that head-up displays, which present necessary information within the line-of-sight, enable more precise manoeuvring to keep flight paths and driving lanes by reducing the shift of the line-of-sight. [25–27] They also reported

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that reducing the driver's line-of-sight shift increased the time spent gazing at the signals and obstacles. Similarly, the use of wearable glasses that display the ultrasound image makes the ultrasound-guided radial artery puncture procedure in children faster and more successful than the conventional method. [28,29]

Recently, advances have been made in projection mapping (PM) technology, which can project precise images onto surfaces. [30] Using this technique, ultrasound images can be projected near the site where the CVC is placed. We hypothesised that projecting ultrasound images near the puncture site would improve the speed and safety of CVC placement performed by inexperienced operators by reducing their line-of-sight shift. Recently, a high-performance eye-tracking system has been available for medical research, and an eye-tracking analysis of gaze patterns during CVC insertion has been reported. [31] In this study, we used eye-tracking technology to analyse resident's gazes during the CVC insertion to evaluate the impact of PM on the operator's gaze behaviour.

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METHODS

This prospective observational study was conducted at the Yokohama City University Medical Center (Yokohama, Japan). The Institutional Review Board of Yokohama City University Medical Center approved this study (B200900073), and all participants provided written informed consent. Volunteer residents were enrolled over 12 months from January to December 2023. The Japanese residency system provides basic training in all fields of clinical medicine during the first 2 years after graduation, followed by 5 years of specialised training for anaesthesia residents. Residents up to 2 years post-graduation (rotating residents post-graduate year: R-PGY 1–2) and anaesthesia residents 3–5 years post-graduation (AR-PGY 3–5) participated in this study.

Study protocol

All participants attended a 1-hour training course on real-time ultrasound-guided central venous catheterisation before the study. This training course included a lecture on ultrasound-guided puncture and hands-on training using the simulator (CVC Puncture Insertion Simulator Ⅱ; Kyoto Kagaku Co. Ltd., Kyoto, Japan) under the supervising physician. Participants were given time to familiarise themselves with an ultrasound machine (EDGE; Sonosite, Inc., Bothell, WA, USA) and received instructions on its

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operation. A 35 mm metal needle was used for puncture (Argyle™ Fukuroi SMAC™ Plus Micro Needle Type). Before the puncture, participants wore a head-mounted eye-tracking system (Tobii Pro Glasses 2; Tobii, Karlsrovagen, Sweden). Their eyes were calibrated using the eye-tracking software (Tobii Pro Lab, Version 1.130) by instructing them to follow a black dot of the small white square card across different areas. After the calibration, participants wore surgical gloves and performed the procedures using the short-axis out-of-plane approach. Figure 1 shows the simulation setup. The participant stood at the simulator's head and the ultrasound machine was placed next to the simulator's right shoulder so that the participant, puncture site, and ultrasound machine were as much on the straight line as possible. In the conventional method, the participant performed the puncture by looking at the screen of the ultrasound machine.

In the PM method, the ultrasound image was projected from the upper right side of the participant onto the flattened drape just caudal to the puncture site by connecting an ultrasound machine to a projector (Light Scene EV-110, Seiko Epson Corporation, Nagano, Japan) (Fig. 2). When viewing the PM image, the ultrasound machine screen was masked, preventing the participant from seeing it. Participants wore the eye-tracking device and performed a total of four punctures, alternating between using PM (PM method) and ultrasound machine screen (conventional method).

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Participants were randomly assigned to start with either the PM or conventional method first (Conventional → PM → Conventional → PM or PM → Conventional → PM → Conventional).

Measurements

The resident's performance was recorded from two directions to allow detailed analysis of the puncture, and the researcher also made thorough observations. The observing researcher verified whether the puncture was successful and ensured the eye-tracking was functioning properly. Ultrasound images were also recorded for analysis. Two blinded researchers who observed the recorded video images after the simulation had been conducted measured all outcomes. The following outcomes were measured for each method: The primary outcome was the procedure time, defined as the time from the application of the ultrasound probe on the puncture field until the successful puncture of the vein that was confirmed by withdrawing 1 mL of water in the simulator's jugular vein. The secondary outcomes were as follows: The task success rate was defined as the number of punctures completed within 10 min from the application of the ultrasound probe to the placement of the guidewire over the total number of punctures for each method (i.e., 2 punctures × 20 residents = 40 punctures for each method). The incidence of arterial and posterior vessel wall puncture was determined by reviewing the recorded ultrasound images by the two blinded researchers. If the needle tip was not fully determined, the needle's depth and the movement of the posterior vessel wall on the ultrasound image were taken as signs of the posterior vessel wall puncture. The first-pass success was defined as the successful puncture of the jugular vein on the first attempt without redirecting the needle, and the first-pass success rate was recorded. The number of needle re-directions was defined as changes in the direction of the needle regardless of whether the needle was removed from the skin or not.

A previous study of the eye-tracking analysis during ultrasound-guided CVC placement revealed that the two most relevant areas of interest (AOIs) included the ultrasound image and the puncture site with its surrounding area. [31] We named these two areas as AOI-UI (ultrasound image) and AOI-PS (puncture site) respectively (Fig. 3) and recorded the time each participant's line-of-sight stayed within these AOIs.

The eye-tracking data were further analysed for the following items:

(i) The fixation-time-image rate (%): Fixation is defined as the gaze fixes at a point in the AOI for over 60 ms. The fixation-time-image rate is the percentage of fixation time within the AOI-UI over the total fixation-time (fixation-time in AOI-UI + fixation-time in AOI-PS) during the puncture. The fixation-time-image rate indicates how focused the participant was on the ultrasound image compared to the puncture site. (ii) Total-fixation-Image/Total-Dwell-Image (%): Dwell-time is the total time during which the participant's gaze was recorded inside the AOI. The dwell time includes the time taken to move the line-of-sight as well as the fixation time. This item is the percentage of the fixation time over the dwell time in the AOI-UI and indicates how focused the participant is on the specific target within the ultrasound image (Fig. 4). The eye-tracking data were automatically calculated by the analysis application after defining the AOI. In this study, we set the same AOI in all cases—at the same location and with the same magnitude—ensuring that no variation in the eye-tracking data was due to differences between measurers.

Calculation of the sample size

Based on the study by Ball et al, a two-tailed Wilcoxon signed-rank test power analysis was conducted based on the primary endpoint of the study, which was the procedure time defined above. [14] Considering the data from the pilot study at our own facility, to possess a power of 80% to avoid type-II error with significance at the 0.05 level, a sample size of 20 residents would be needed to detect a 50% difference for the procedure time between the PM method and conventional method, using R package 'pwrss' (Bulus, M.

[2023]. pwrss: Statistical Power and Sample Size Calculation Tools. R package version 0.3.1. https://CRAN.R-project.org/package=pwrss). A total sample size of 22 participants (20 plus 2) was estimated, considering an expected 10–20% missing data due to eye-tracking measurement errors or other factors.

Statistical analysis

Wilcoxon signed-rank tests were used for nonparametric paired samples (the procedure time, the number of needle re-directions, the fixation-time-image rate, and the Total-fixation-Image/Total-Dwell-Image) and exact McNemar's tests were employed to compare the task success rate, first-pass success rate, and the incidence of artery and posterior vessel wall puncture. Additionally, the univariate correlation between the procedure time and puncture experience was assessed using Spearman's rank correlation. The level of significance was set at $p<0.05$. All analyses were performed using IBM SPSS Statistics, Version 29.0.2.0 (Armonk, NY, USA).

Patient and public involvement

None.

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RESULTS

Twenty-two residents, each having less than 50 CVC puncture experiences, were recruited and participated in the study; however, two participants dropped out owing to incomplete eye-tracking data. Therefore, the data of 20 residents were subject to final analysis. Less experienced trainees (R-PGY 1–2) comprised 60% of the participants (12/20), including five residents with no prior CVC puncture experience on actual patients (Table 1).

The procedure time was significantly shorter in the PM method than in the conventional method (median [interquartile range]: 22.5 [15.5–30.6] s vs 30.0 [20.4–95.4] s; p=0.02) (Fig. 5-a). The success rate was 100% in both methods, and no arterial puncture occurred in either. Posterior vessel wall punctures occurred in five of the 20 participants in the conventional method, but not in the PM method (0% vs. 25%; p=0.02). No significant differences were observed in the first-pass-success rate (62.5% vs. 52.5%; p=0.45) and the number of needle re-directions (1.5 [1.0–1.9] vs 1.5 [1.0–2.4]; p=0.26). No significant correlation existed between the procedure time and puncture experience (PM method, r=0.07, p=0.78; conventional method, r=0.13, p=0.58). The fixation-time-image rate was significantly higher in the PM method (61.6 [55.0–69.2]% vs. 45.7 [34.1–54.5]%; p<0.01) (Fig. 5-b). Total-fixation-Image/Total-Dwell-Image was significantly

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higher in the PM method (92.7 [89.6–94.5]% vs 87.8 [73.5–93.7]%; p=0.01) (Fig. 5-c). Two researchers reviewed the eye-tracking video images and confirmed that, in all participants, the puncture site was constantly captured within the AOI-UI during the PM methods but not during the conventional method.

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DISCUSSION

The results of this study demonstrated that the PM method enables residents to perform CVC punctures faster and with a lower incidence of posterior vessel wall punctures than the conventional method. These findings indicate that the PM method facilitates the identification of the needle tip using ultrasound and improves the hand-eye coordination required for the CVC puncture. This would contribute to safer puncture in the real clinical settings.

In contrast, no differences were observed between the two methods regarding the overall and the first-pass success rates, incidence of arterial puncture, and number of needle re-direction. Our results of the 100% overall success rate with no arterial puncture suggest that our simulator is relatively easy to elucidate any possible difference between the two methods (*i.e.*, ceiling effect). The first-pass success using the short-axis out-of-plane approach requires the determination of the adequate puncture site and the right direction of the needle. The ultrasound plays a role in the puncture site by identifying the position of the jugular vein, but not in the right direction of the needle because the needle is visualised only after it is advanced into the tissue. This limited role of ultrasound may account for the lack of difference in the first-pass success rate between the two methods. Additionally, participants were possibly familiar with the simulator due to the training

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conducted immediately before.

The eye-tracking data revealed that, compared to the conventional method, the PM method was associated with longer fixation in the ultrasound image relative to the puncture site than the conventional method. Moreover, when the line-of-sight was within the ultrasound image, the PM method promoted fixation on the key structure more than the conventional method. Longer fixation indicates that the operator focused longer on the region of interest. Therefore, our results suggest that, compared to the conventional method, the PM method helps our participants to focus more on the ultrasound image than the puncture site as well as on the key structure within the ultrasound image. These characteristics are similar to those of the skilled operators demonstrated by previous studies of vessel punctures and nerve blocks and may account for shorter procedure time and lower incidence of posterior vessel wall punctures demonstrated in this study. [32,33]

Two mechanisms may account for our results of the eye-tracking analysis. First, the shorter distance between the ultrasound image and the puncture site with the PM method reduced the workload associated with the shift of the line-of-sight. Second, with the PM method, the puncture site was always captured within the AOI-UI. In healthy individuals, the horizontal and vertical viewing angles are approximately 200° and 130°, respectively.

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[34] The viewing angle of the eye-tracking camera is 82° and 52° respectively; therefore, what was visible in the eye-tracking video image was likely to be in the participants' field of view as well. Thus, it is likely that the PM method allowed our participants to receive some information about the direction and depth of the needle from their peripheral field of view even when their line-of-sight was on the ultrasound image, enabling more fixation on the ultrasound image and also on the key structure within it. [35] In contrast, in the conventional method, the ultrasound image and the puncture site were far apart, and the operator had to consciously move the line-of-sight between the two sites, which affected fixation.

This study had some limitations. First, the study was conducted in a simulated environment, which did not fully replicate the real-world situation. The simulator may be easier to puncture than real patients or may become accustomed more quickly. This aspect was not considered in this study. It remains unclear to what extent the differences in the procedure time are clinically significant. Further studies on the efficacy of PM on actual patients are warranted. Secondly, the definition of fixation may differ according to what is being observed, and no evidence exists for ultrasound-guided procedures. We defined fixation as 60 ms or longer in this study based on the previous study for reading and observing objects; however, the average fixation for the scene perception has been

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reported to be 220 ms to 360 ms. [36,37] Thirdly, all our participants had less than 50 CVC placement experiences and were considered novices according to previous studies. [22] Slight differences in the presentation location of ultrasound images may not considerably affect a skilled operator. According to previously published findings, the gaze pattern during the CVC placement differs between experienced and inexperienced operators; therefore, our results may not be applicable to individuals with more experiences in performing CVC placement. [31]

In summary, our results suggests that the presentation of ultrasound images close to the puncture field by our PM device facilitates the safe real-time ultrasound-guided CVC puncture by novice operators. The finding has the potential to be applied to various other ultrasound-guided procedures. With future technological advances, such as the miniaturisation of projectors, this method will evolve for daily use.

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Contributions: AM and AF are joint first authors. AM, AF, Kyota N, TA, KT and HS conceptualised the study. AM, AF, HS, DK, KM, and HS designed the study and collected data. AM, AF, TA and HS were involved in the analysis of the data. AM, AF, and HS drafted the manuscript. HK, Kazue N, and TG revised the manuscript. All authors contributed to data interpretation, reviewed the successive drafts and approved the final version of the manuscript. HS takes responsibility for the overall content as guarantor.

Patient consent for publication: Not applicable.

Ethics approval: This study was approved by the Institutional Review Board of Yokohama City University Medical Center (B200900073)

Data availability statement: Data are available upon reasonable request. The data underlying this article will be shared on reasonable request to the corresponding author.

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Table 1 Demographic variables of participating residents.

Participant characteristic variables	n = 20 (%)
Clinical year	
R-PGY 1	2 (10)
R-PGY 2	10 (59)
AR-PGY 3	5 (25)
AR-PGY 4	2 (10)
AR-PGY 5	1 (5)
Prior experience of CVC insertions (times)	
<10	12 (60)
11–20	5 (25)
21–30	1 (10)
31–40	1 (10)
41–50	1 (10)

AR, anaesthesia resident; CVC, central venous catheter; PGY, post-graduate year; R, resident

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Figure legends

Fig 1. Setting of the simulation.

The simulator was placed on the operating table. The ultrasound machine was placed next to the simulator's right shoulder, and the projector was behind the participant. CVC, central venous catheter

Fig 2. Projection mapping setup

The projector was used to project the ultrasound image from the upper right of the participant, very close to the puncture site. The images of the projection mapping are highly accurate and comparable to the ultrasound machine screen in CVC puncture. CVC, central venous catheter

Fig 3. Eye-tracking analysis

Left panel: Analysis of PM Method

Set AOI to puncture site and ultrasound image (projection mapping)

Right panel: Analysis of conventional method

Set AOI to puncture site and ultrasound image (ultrasound machine screen)

AOI, area of interest; AOI-UI, AOI-ultrasound image; AOI-PS, AOI-puncture site

Fig 4. Formula for fixation-time-image rate and dwell-time rate

AOI, area of interest; AOI-UI, AOI-ultrasound image; AOI-PS AOI-puncture site

Fig 5.

a: The procedure time was significantly shorter in the PM method ($p=0.02$).

b: The Fixation-time rate was significantly higher in the PM method ($p<0.01$).

c: Total-fixation-Image/Total-Dwell-Image was significantly higher in the PM method ($p=0.01$)

PM, projection mapping

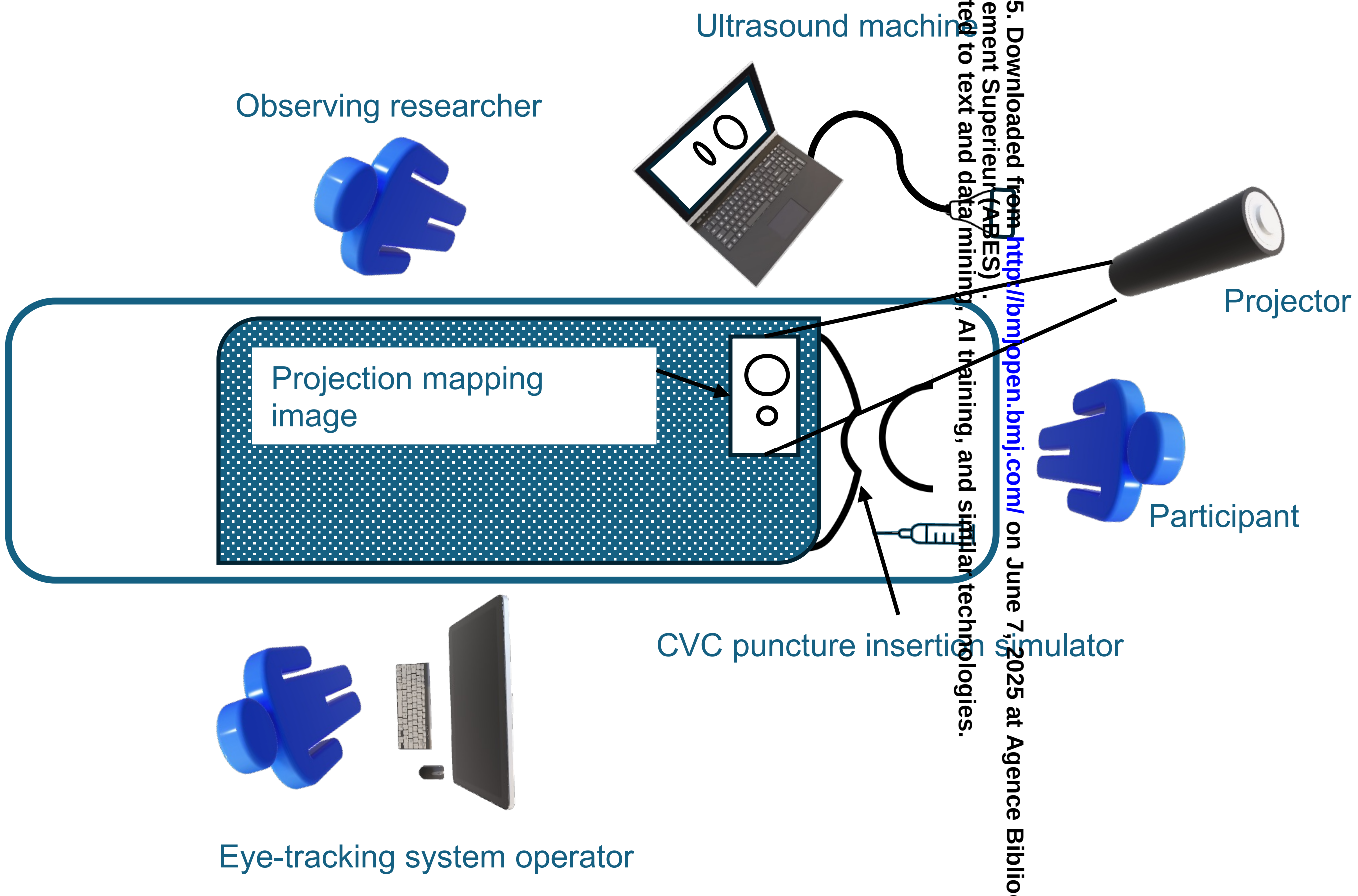
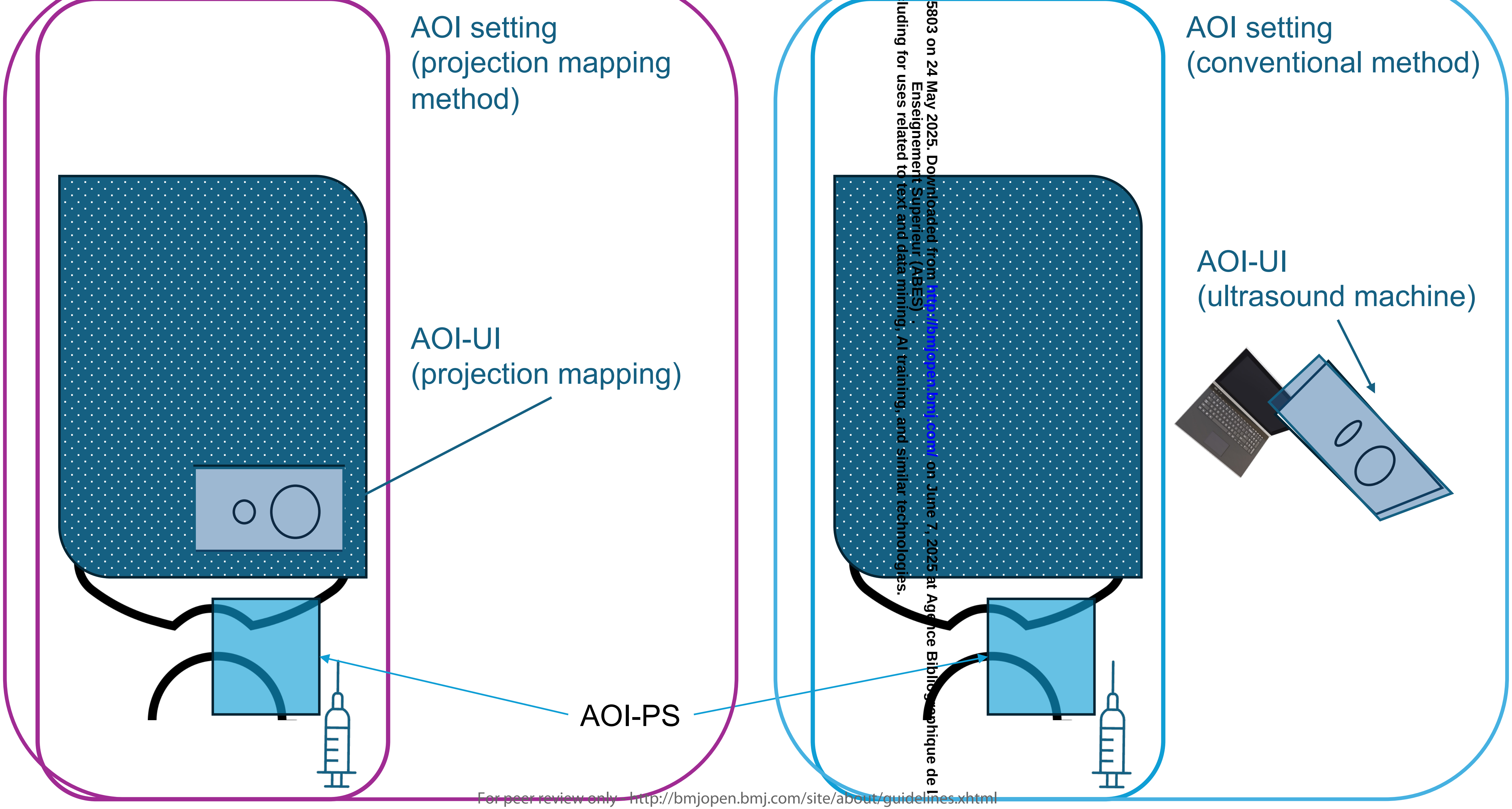

Ultrasound machine
Observing researcher
Projector
Projection mapping image
Participant
CVC puncture insertion simulator
Eye-tracking system operator

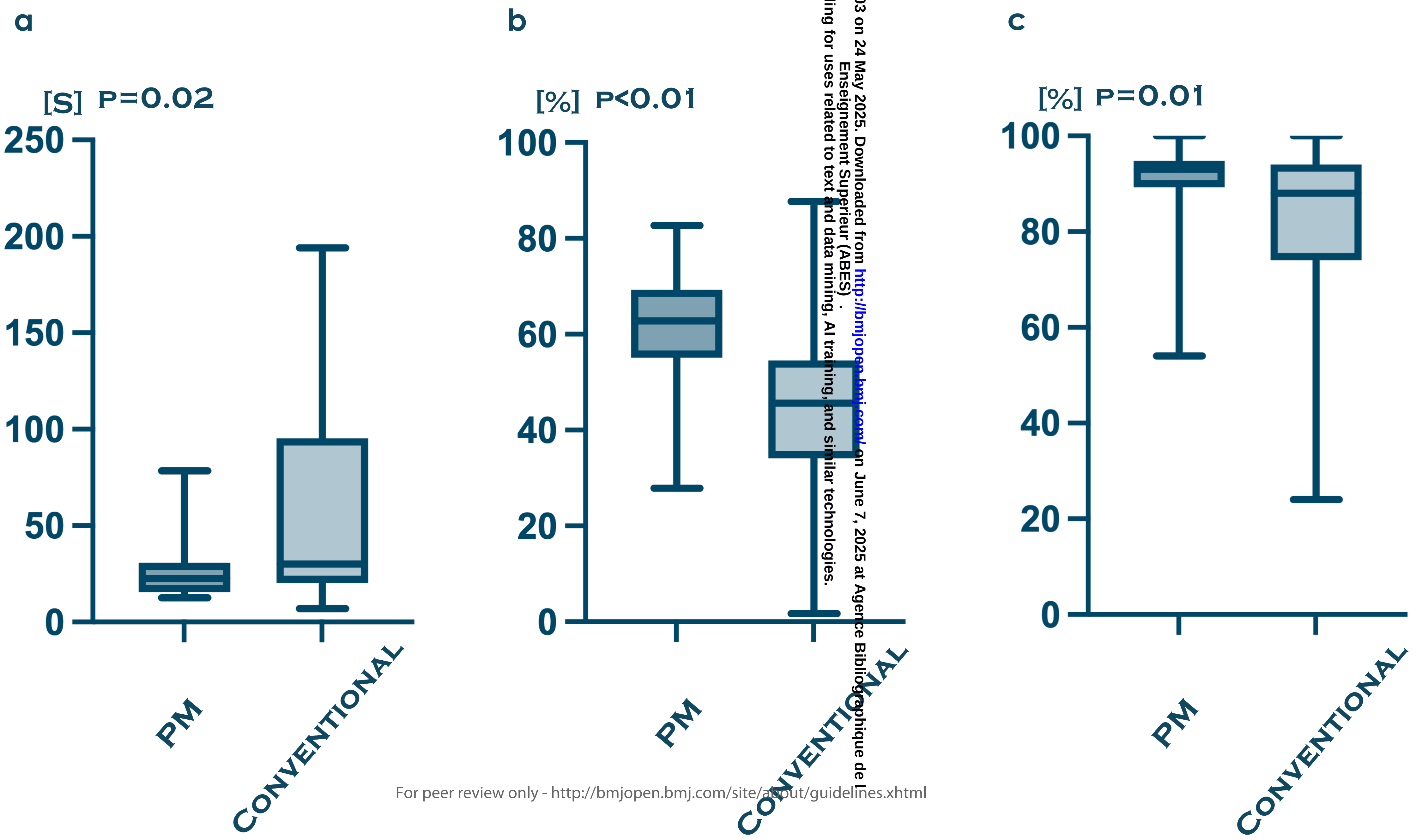
Fig 2. Projection mapping setup
The projector was used to project the ultrasound image from the upper right of the participant, very close to the puncture site. The images of the projection mapping are highly accurate and comparable to the ultrasound machine screen in CVC puncture. CVC, central venous catheter

201x151mm (300 x 300 DPI)


AOI setting
(projection mapping
method)
AOI-UI
(projection mapping)
AOI-PS
AOI setting
(conventional method)
AOI-UI
(ultrasound machine)

$$\text{Fixation-time-image rate (\%)} = \frac{\text{Fixation-time AOI-UI}}{\text{Fixation-time AOI-UI} + \text{Fixation-time AOI-PS}} \times 100$$

$$\text{Dwell-time-image rate (\%)} = \frac{\text{Dwell-time AOI-UI}}{\text{Dwell-time AOI-UI} + \text{Dwell-time AOI-PS}} \times 100$$


a
[S] P=0.02
250
200
150
100
50
0
PM
CONVENTIONAL
b
[%] P<0.01
100
80
60
40
20
0
PM
CONVENTIONAL
c
[%] P=0.01
100
80
60
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PM
CONVENTIONAL

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Enhancing quality and safety of central venous catheter insertion using projection mapping: a prospective observational simulation study with eye-tracking glasses

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Keywords: Central venous catheter insertion; Eye-tracking analysis; Medical simulation; Projection mapping; Realtime ultrasound guidance

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ABSARACT

Objectives

We aimed to evaluate the effect of projection mapping (PM) on the quality and safety of central venous catheter (CVC) insertion under real-time ultrasound guidance.

Design

Prospective, observational, simulation study.

Setting

This study was conducted at the Yokohama City University Medical Center (Yokohama, Japan). Volunteer residents were enrolled over 12 months from January to December 2023.

Participants and methods

Twelve rotating residents (post-graduation year [PGY] 1 and 2) and eight anaesthesia residents (PGY 3–5) placed the CVC in the internal jugular vein in a simulator under the real-time ultrasound guidance using the short-axis out-of-plane approach. The ultrasound image was provided either just caudad to the puncture site using the PM method or on the monitor of the ultrasound machine (conventional method) placed next to the simulator's right shoulder. Each resident performed four punctures alternating between the PM and conventional methods, and the first method for each resident was

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chosen randomly. Eye-tracking analysis was also used to evaluate differences in gaze behaviour.

Primary and secondary outcome measures

The primary outcome was the procedure time defined as the time from the application of the ultrasound probe on the puncture field until successful puncture of the vein. The secondary outcomes were incidence of complications and eye-tracking analysis data.

Results

The time to complete the line placement was significantly shorter for the PM than for the conventional method [median (interquartile range) 22.5 (15.5–30.6) s vs 30.0 (20.4–95.4) s; p=0.02, Wilcoxon's singed-rank test]. The incidence of posterior vessel wall puncture was significantly lower in the PM method (0% vs 25%; p=0.02, McNemar's test). Eye-tracking analysis revealed that the percentage of time spent gazing at the ultrasound image was higher in the PM than in the conventional method (61.6% [55.0–69.2] vs. 45.7% [34.1–54.5]; p<0.01).

Conclusions

The PM method facilitates ultrasound-guided CVC placement while preventing excessive needle advancement in the inexperienced operators. This was accompanied by enhanced fixation of the participants' line-of-sight on the ultrasound image.

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Strengths and limitations of this study

- This study used eye-tracking to show how the operator's gaze shifts during central venous puncture.
- Novices with limited and relatively uniform experience of CVC placement participated in the study.
- This study was conducted in a simulated environment, which did not fully replicate the real-world situation.
- The basic settings for ere-tracking analysis vary, and the most suitable settings for central venous puncture remain unclear.

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INTRODUCTION

Real-time ultrasound guidance has become the standard practice for the central venous catheter (CVC) placement in the internal jugular vein. [1–9] In this procedure, the short-axis out-of-plane approach is more common than the long-axis in-plane approach. [10–14] For the short-axis out-of-plane approach, the operator slides the ultrasound probe in the caudad direction while advancing the puncture needle so that the needle tip is always located. This requires a certain level of skill, and some investigators have raised a concern that the risk of excessively deep needle advancement may be higher than that in the conventional landmark methods, especially in the hands of inexperienced operators. [15–17] This risk may lead to posterior vessel wall puncture, and serious complications such as vertebral artery puncture and pneumothorax may ensue. [18–24] In the real-time ultrasound-guided method, the operator must alternately observe the ultrasound image and the puncture site, which are located separately. Shifting the line-of-sight may increase the workload and interfere with the hand-eye coordination, especially for the inexperienced operators. Indeed, recent studies on aviation safety and automobile driving have shown that head-up displays, which present necessary information within the line-of-sight, enable more precise manoeuvring to keep flight paths and driving lanes by reducing the shift of the line-of-sight. [25–27] They also reported that reducing the driver's line-of-sight shift increased the time spent gazing at the signals and obstacles. Similarly, the use of wearable glasses that display the ultrasound image makes the ultrasound-guided radial artery puncture procedure in children faster and more successful than the conventional method. [28,29]

Recently, advances have been made in projection mapping (PM) technology, which can project precise images onto surfaces. [30] Using this technique, ultrasound images can be projected near the site where the CVC is placed. We hypothesised that projecting ultrasound images near the puncture site would improve the speed and safety of CVC placement performed by inexperienced operators by reducing their line-of-sight shift. Recently, a high-performance eye-tracking system has been available for medical research, and an eye-tracking analysis of gaze patterns during CVC insertion has been reported. [31] In this study, we used eye-tracking technology to analyse resident's gazes during the CVC insertion to evaluate the impact of PM on the operator's gaze behaviour.

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METHODS

This prospective observational study was conducted at the Yokohama City University Medical Center (Yokohama, Japan). The Institutional Review Board of Yokohama City University Medical Center approved this study (B200900073), and all participants provided written informed consent. Volunteer residents were enrolled over 12 months from January to December 2023. The Japanese residency system provides basic training in all fields of clinical medicine during the first 2 years after graduation, followed by 5 years of specialised training for anaesthesia residents. Residents up to 2 years post-graduation (rotating residents post-graduate year: R-PGY 1–2) and anaesthesia residents 3–5 years post-graduation (AR-PGY 3–5) participated in this study.

Study protocol

All participants attended a 1-hour training course on real-time ultrasound-guided central venous catheterisation before the study. This training course included a lecture on ultrasound-guided puncture and hands-on training using the simulator (CVC Puncture Insertion Simulator Ⅱ; Kyoto Kagaku Co. Ltd., Kyoto, Japan) under the supervising physician. Participants were given time to familiarise themselves with an ultrasound machine (EDGE; Sonosite, Inc., Bothell, WA, USA) and received instructions on its

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operation. A 35 mm metal needle was used for puncture (Argyle™ Fukuroi SMAC™ Plus Micro Needle Type). Before the puncture, participants wore a head-mounted eye-tracking system (Tobii Pro Glasses 2; Tobii, Karlsrovagen, Sweden). Their eyes were calibrated using the eye-tracking software (Tobii Pro Lab, Version 1.130) by instructing them to follow a black dot of the small white square card across different areas. After the calibration, participants wore surgical gloves and performed the procedures using the short-axis out-of-plane approach. Figure 1 shows the simulation setup. The participant stood at the simulator's head and the ultrasound machine was placed next to the simulator's right shoulder so that the participant, puncture site, and ultrasound machine were as much on the straight line as possible. In the conventional method, the participant performed the puncture by looking at the screen of the ultrasound machine.

In the PM method, the ultrasound image was projected from the upper right side of the participant onto the flattened drape just caudal to the puncture site by connecting an ultrasound machine to a projector (Light Scene EV-110, Seiko Epson Corporation, Nagano, Japan) (Figure 2). When viewing the PM image, the ultrasound machine screen was masked, preventing the participant from seeing it. In this study, all participants performed both methods by a cross-over design starting with either Conventional or PM. In addition, all participants were novices with less than 50 cases of experience in

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performing ultrasound guided puncture and CVC placement, in which we believe our participants would be homogeneous. Participants wore the eye-tracking device and performed a total of four punctures, alternating between using PM (PM method) and ultrasound machine screen (conventional method). Participants were randomly assigned to start with either PM method or conventional method first (Conventional → PM → Conventional → PM or PM → Conventional → PM → Conventional).

Measurements

The resident's performance was recorded from two directions to allow detailed analysis of the puncture, and the researcher also made thorough observations. The observing researcher verified whether the puncture was successful and ensured the eye-tracking was functioning properly. Ultrasound images were also recorded for analysis. Two blinded researchers who observed the recorded video images after the simulation had been conducted measured all outcomes. The following outcomes were measured for each method: The primary outcome was the procedure time, defined as the time from the application of the ultrasound probe on the puncture field until the successful puncture of the vein that was confirmed by withdrawing 1 mL of water in the simulator's jugular vein. The secondary outcomes were as follows: The task success rate was defined as

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the number of punctures completed within 10 min from the application of the ultrasound probe to the placement of the guidewire over the total number of punctures for each method (i.e., 2 punctures × 20 residents = 40 punctures for each method). The incidence of arterial and posterior vessel wall puncture was determined by reviewing the recorded ultrasound images by the two blinded researchers. If the needle tip was not fully determined, the needle's depth and the movement of the posterior vessel wall on the ultrasound image were taken as signs of the posterior vessel wall puncture. The first-pass success was defined as the successful puncture of the jugular vein on the first attempt without redirecting the needle, and the first-pass success rate was recorded. The number of needle re-directions was defined as changes in the direction of the needle regardless of whether the needle was removed from the skin or not.

A previous study of the eye-tracking analysis during ultrasound-guided CVC placement revealed that the two most relevant areas of interest (AOIs) included the ultrasound image and the puncture site with its surrounding area. [31] We named these two areas as AOI-UI (ultrasound image) and AOI-PS (puncture site) respectively (Figure 3) and recorded the time each participant's line-of-sight stayed within these AOIs.

The eye-tracking data were further analysed for the following items:

(i) The fixation-time-image rate (%): Fixation is defined as the gaze fixes at a point in the

AOI for over 60 ms. The fixation-time-image rate is the percentage of fixation time within the AOI-UI over the total fixation-time (fixation-time in AOI-UI + fixation-time in AOI-PS) during the puncture. The fixation-time-image rate indicates how focused the participant was on the ultrasound image compared to the puncture site. (ii) Total-fixation-Image/Total-Dwell-Image (%): Dwell-time is the total time during which the participant's gaze was recorded inside the AOI. The dwell time includes the time taken to move the line-of-sight as well as the fixation time. This item is the percentage of the fixation time over the dwell time in the AOI-UI and indicates how focused the participant is on the specific target within the ultrasound image (Figure 4). The eye-tracking data were automatically calculated by the analysis application after defining the AOI. In this study, we set the same AOI in all cases—at the same location and with the same magnitude—ensuring that no variation in the eye-tracking data was due to differences between measurers.

Calculation of the sample size

Based on the study by Ball et al, a two-tailed Wilcoxon signed-rank test power analysis was conducted based on the primary endpoint of the study, which was the procedure time defined above. [14] Considering the data from the pilot study at our own facility, to possess a power of 80% to avoid type-II error with significance at the 0.05 level, a sample size of 20 residents would be needed to detect a 50% difference for the procedure time between the PM method and conventional method, using R package 'pwrss' (Bulus, M. [2023]. pwrss: Statistical Power and Sample Size Calculation Tools. R package version 0.3.1. https://CRAN.R-project.org/package=pwrss). A total sample size of 22 participants (20 plus 2) was estimated, considering an expected 10–20% missing data due to eye-tracking measurement errors or other factors.

Statistical analysis

Wilcoxon signed-rank tests were used for nonparametric paired samples (the procedure time, the number of needle re-directions, the fixation-time-image rate, and the Total-fixation-Image/Total-Dwell-Image) and exact McNemar's tests were employed to compare the task success rate, first-pass success rate, and the incidence of artery and posterior vessel wall puncture. Additionally, the univariate correlation between the procedure time and puncture experience was assessed using Spearman's rank correlation. The level of significance was set at $p<0.05$. All analyses were performed using IBM SPSS Statistics, Version 29.0.2.0 (Armonk, NY, USA).

Patient and public involvement

None.

RESULTS

Twenty-two residents, each having less than 50 CVC puncture experiences, were recruited and participated in the study; however, two participants dropped out owing to incomplete eye-tracking data. Therefore, the data of 20 residents were subject to final analysis. Less experienced trainees (R-PGY 1–2) comprised 60% of the participants (12/20), including five residents with no prior CVC puncture experience on actual patients (Table 1).

The procedure time was significantly shorter in the PM method than in the conventional method (median [interquartile range]: 22.5 [15.5–30.6] s vs 30.0 [20.4–95.4] s; p=0.02) (Figure 5a). The success rate was 100% in both methods, and no arterial puncture occurred in either. Posterior vessel wall punctures occurred in five of the 20 participants in the conventional method, but not in the PM method (0% vs. 25%; p=0.02). No significant differences were observed in the first-pass-success rate (62.5% vs. 52.5%; p=0.45) and the number of needle re-directions (1.5 [1.0–1.9] vs 1.5 [1.0–2.4]; p=0.26). No significant correlation existed between the procedure time and puncture experience

(PM method, r=0.07, p=0.78; conventional method, r=0.13, p=0.58). The fixation-time-image rate was significantly higher in the PM method (61.6 [55.0–69.2]% vs. 45.7 [34.1–54.5]%; p<0.01) (Figure 5b). Total-fixation-Image/Total-Dwell-Image was significantly higher in the PM method (92.7 [89.6–94.5]% vs 87.8 [73.5–93.7]%; p=0.01) (Figure 5c). Two researchers reviewed the eye-tracking video images and confirmed that, in all participants, the puncture site was constantly captured within the AOI-UI during the PM methods but not during the conventional method.

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DISCUSSION

The results of this study demonstrated that the PM method enables residents to perform CVC punctures faster and with a lower incidence of posterior vessel wall punctures than the conventional method. These findings indicate that the PM method facilitates the identification of the needle tip using ultrasound and improves the hand-eye coordination required for the CVC puncture. This would contribute to safer puncture in the real clinical settings.

In contrast, no differences were observed between the two methods regarding the overall and the first-pass success rates, incidence of arterial puncture, and number of needle re-direction. Our results of the 100% overall success rate with no arterial puncture suggest that our simulator is relatively easy to elucidate any possible difference between the two methods (*i.e.*, ceiling effect). The first-pass success using the short-axis out-of-plane approach requires the determination of the adequate puncture site and the right direction of the needle. The ultrasound plays a role in the puncture site by identifying the position of the jugular vein, but not in the right direction of the needle because the needle is visualised only after it is advanced into the tissue. This limited role of ultrasound may account for the lack of difference in the first-pass success rate between the two methods. Additionally, participants were possibly familiar with the simulator due to the training

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conducted immediately before.

The eye-tracking data revealed that, compared to the conventional method, the PM method was associated with longer fixation in the ultrasound image relative to the puncture site than the conventional method. Moreover, when the line-of-sight was within the ultrasound image, the PM method promoted fixation on the key structure more than the conventional method. Longer fixation indicates that the operator focused longer on the region of interest. Therefore, our results suggest that, compared to the conventional method, the PM method helps our participants to focus more on the ultrasound image than the puncture site as well as on the key structure within the ultrasound image. These characteristics are similar to those of the skilled operators demonstrated by previous studies of vessel punctures and nerve blocks and may account for shorter procedure time and lower incidence of posterior vessel wall punctures demonstrated in this study. [32,33]

Two mechanisms may account for our results of the eye-tracking analysis. First, the shorter distance between the ultrasound image and the puncture site with the PM method reduced the workload associated with the shift of the line-of-sight. Second, with the PM method, the puncture site was always captured within the AOI-UI. In healthy individuals, the horizontal and vertical viewing angles are approximately 200° and 130°, respectively.

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[34] The viewing angle of the eye-tracking camera is 82° and 52° respectively; therefore, what was visible in the eye-tracking video image was likely to be in the participants' field of view as well. Thus, it is likely that the PM method allowed our participants to receive some information about the direction and depth of the needle from their peripheral field of view even when their line-of-sight was on the ultrasound image, enabling more fixation on the ultrasound image and also on the key structure within it. [35] In contrast, in the conventional method, the ultrasound image and the puncture site were far apart, and the operator had to consciously move the line-of-sight between the two sites, which affected fixation.

This study had some limitations. First, the study was conducted in a simulated environment, which did not fully replicate the real-world situation. The simulator may be easier to puncture than real patients or may become accustomed more quickly. This aspect was not considered in this study. It remains unclear to what extent the differences in the procedure time are clinically significant. Further studies on the efficacy of PM on actual patients are warranted. Secondly, the definition of fixation may differ according to what is being observed, and no evidence exists for ultrasound-guided procedures. We defined fixation as 60 ms or longer in this study based on the previous study for reading and observing objects; however, the average fixation for the scene perception has been reported to be 220 ms to 360 ms. [36,37] Thirdly, all our participants had less than 50 CVC placement experiences and were considered novices according to previous studies. [22] Slight differences in the presentation location of ultrasound images may not considerably affect a skilled operator. According to previously published findings, the gaze pattern during the CVC placement differs between experienced and inexperienced operators; therefore, our results may not be applicable to individuals with more experiences in performing CVC placement. [31]

In summary, our results suggests that the presentation of ultrasound images close to the puncture field by our PM device facilitates the safe real-time ultrasound-guided CVC puncture by novice operators. The finding has the potential to be applied to various other ultrasound-guided procedures. With future technological advances, such as the miniaturisation of projectors, this method will evolve for daily use.

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Contributors: AM and AF are joint first authors. AM, AF, Kyota N, TA, KT and HS conceptualised the study. AM, AF, HS, DK, KM, and HS designed the study and collected data. AM, AF, TA and HS were involved in the analysis of the data. AM, AF, and HS drafted the manuscript. HK, Kazue N, and TG revised the manuscript. All authors contributed to data interpretation, reviewed the successive drafts and approved the final version of the manuscript. HS takes responsibility for the overall content as guarantor.

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Patient consent for publication: Not applicable.

Data availability statement: The data underlying this article will be shared on reasonable request to the corresponding author.

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Table 1. Demographic variables of participating residents

Participant characteristic variables	**n = 20 (%)**
Clinical year	
R-PGY 1	2 (10)
R-PGY 2	10 (59)
AR-PGY 3	5 (25)
AR-PGY 4	2 (10)
AR-PGY 5	1 (5)
Prior experience of CVC insertions (times)	
<10	12 (60)
11–20	5 (25)
21–30	1 (10)
31–40	1 (10)
41–50	1 (10)

AR, anaesthesia resident; CVC, central venous catheter; PGY, post-graduate year; R, resident.

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FIGURE LEGENDS

Figure 1. Setting of the simulation

The simulator was placed on the operating table. The ultrasound machine was placed next to the simulator's right shoulder, and the projector was behind the participant. CVC, central venous catheter

Figure 2. Projection mapping setup

The projector was used to project the ultrasound image from the upper right of the participant, very close to the puncture site. The images of the projection mapping are highly accurate and comparable to the ultrasound machine screen in CVC puncture. The pictured individual has provided consent for publication of the image. CVC, central venous catheter

Figure 3. Eye-tracking analysis

Left panel: Analysis of PM Method

Set AOI to puncture site and ultrasound image (projection mapping)

Right panel: Analysis of conventional method

Set AOI to puncture site and ultrasound image (ultrasound machine screen)

AOI, area of interest; AOI-UI, AOI-ultrasound image; AOI-PS, AOI-puncture site

Figure 4. Formula for fixation-time-image rate and dwell-time rate

AOI, area of interest; AOI-UI, AOI-ultrasound image; AOI-PS AOI-puncture site

Figure 5. Comparisons between PM and conventional methods

(a): The procedure time was significantly shorter in the PM method (p=0.02).

(b): The Fixation-time rate was significantly higher in the PM method (p<0.01).

(c): Total-fixation-Image/Total-Dwell-Image was significantly higher in the PM method (p=0.01)

PM, projection mapping.

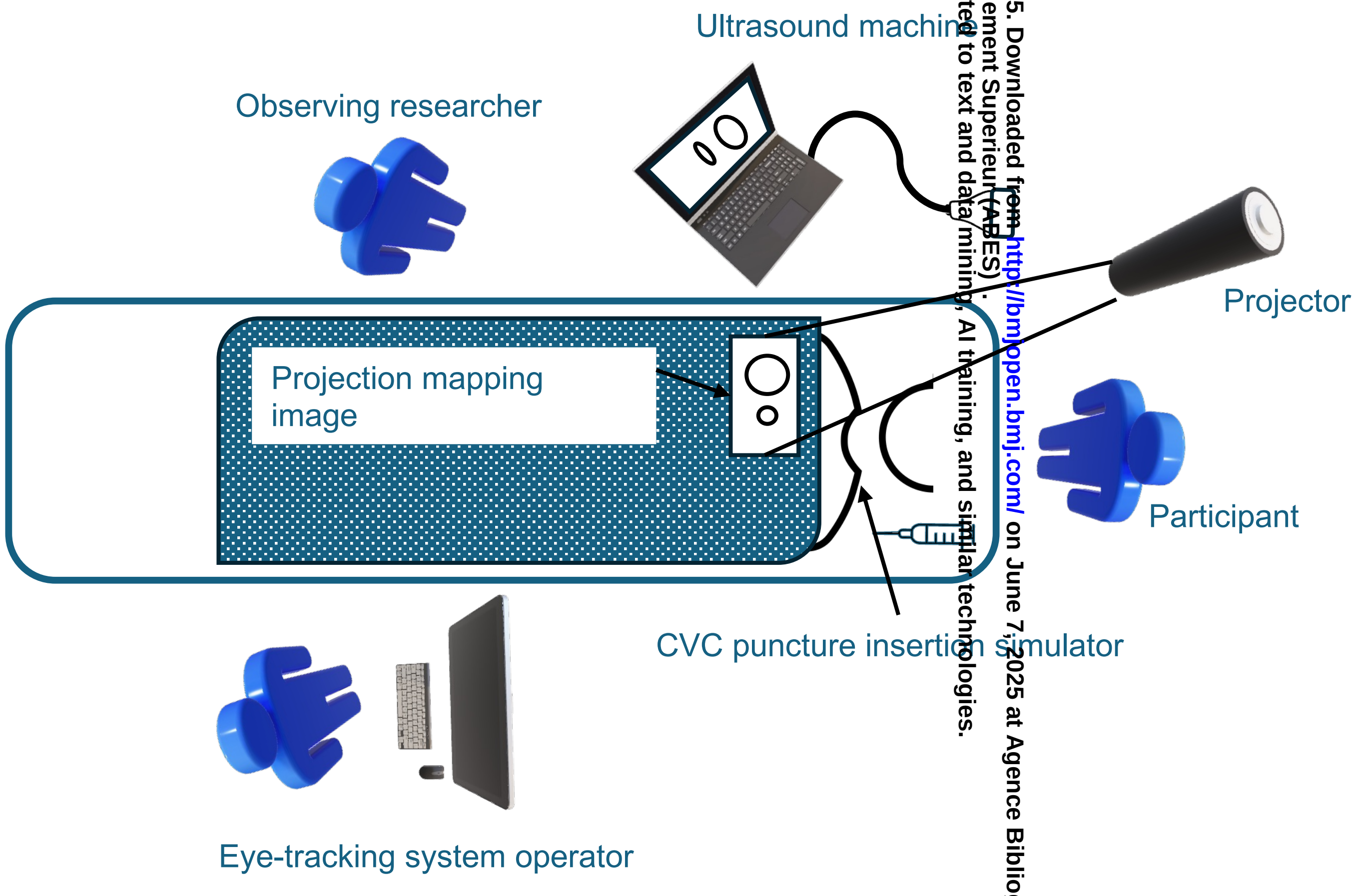
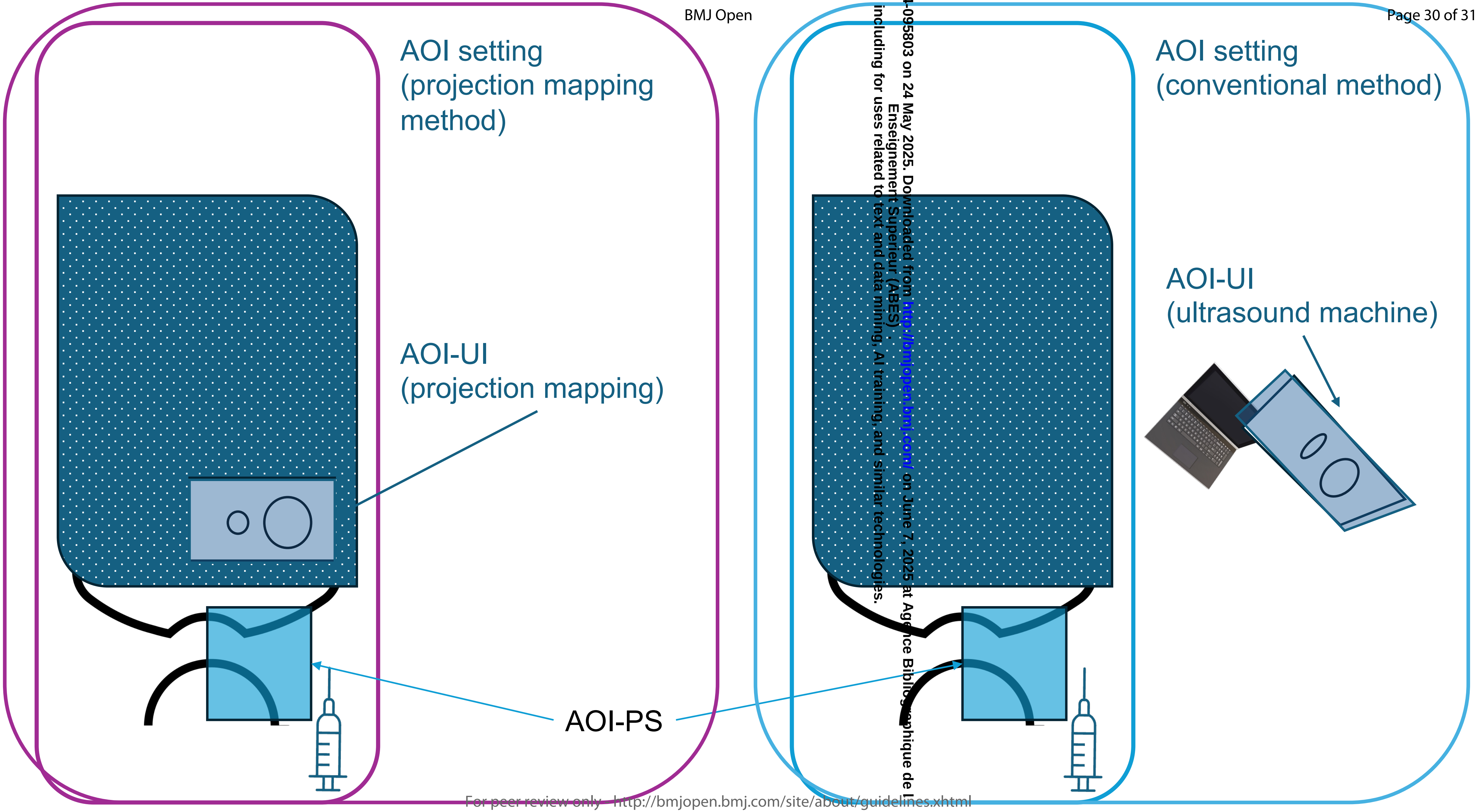

Ultrasound machine
Observing researcher
Projector
Projection mapping image
Participant
CVC puncture insertion simulator
Eye-tracking system operator

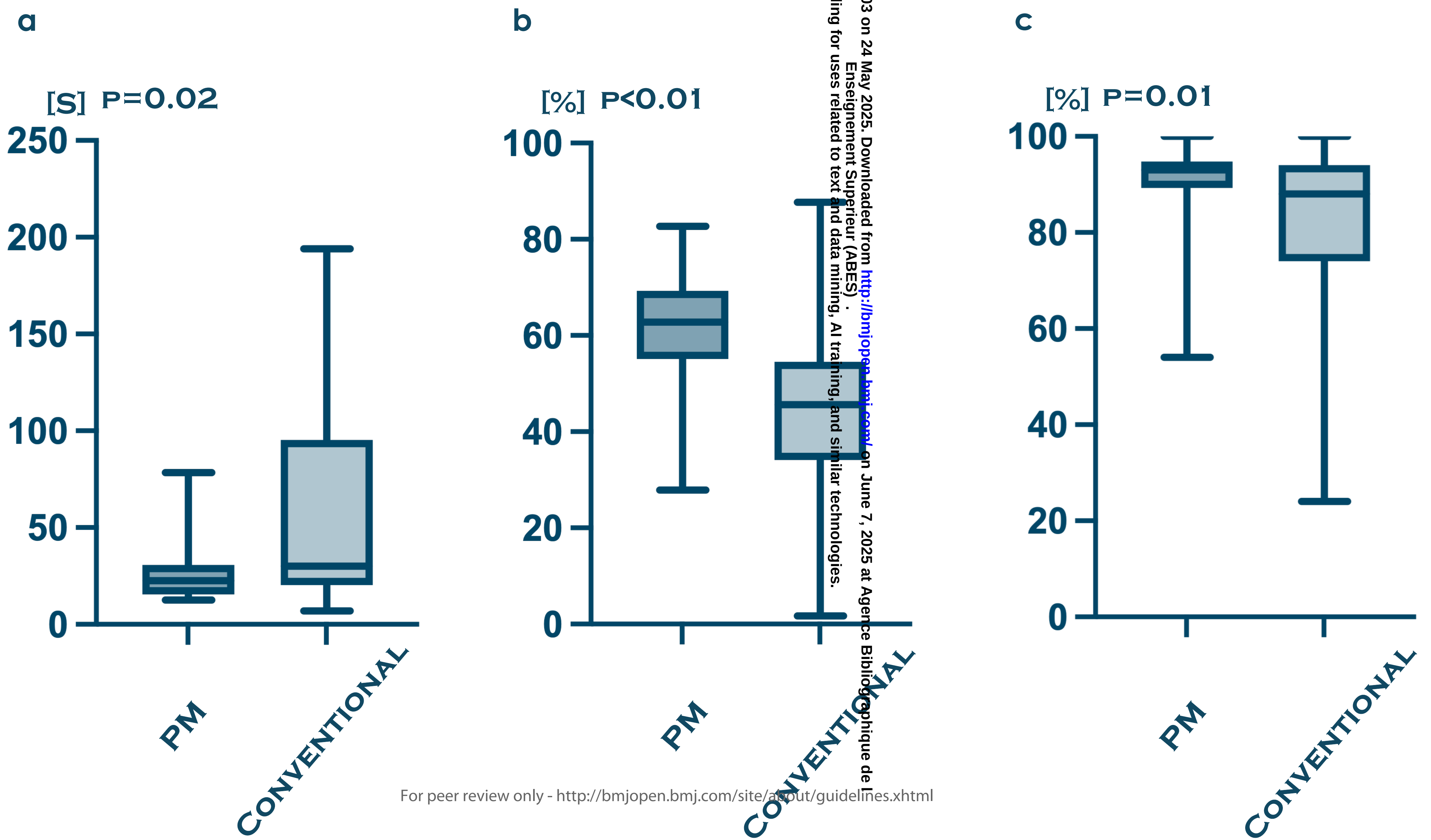
Fig 2. Projection mapping setup
The projector was used to project the ultrasound image from the upper right of the participant, very close to the puncture site. The images of the projection mapping are highly accurate and comparable to the ultrasound machine screen in CVC puncture. CVC, central venous catheter

201x151mm (300 x 300 DPI)


AOI setting
(projection mapping
method)
AOI-UI
(projection mapping)
AOI-PS
AOI setting
(conventional method)
AOI-UI
(ultrasound machine)

$$\text{Fixation-time-image rate (\%)} = \frac{\text{Fixation-time AOI-UI}}{\text{Fixation-time AOI-UI} + \text{Fixation-time AOI-PS}} \times 100$$

$$\text{Dwell-time-image rate (\%)} = \frac{\text{Dwell-time AOI-UI}}{\text{Dwell-time AOI-UI} + \text{Dwell-time AOI-PS}} \times 100$$


a
[S] P=0.02
250
200
150
100
50
0
PM
CONVENTIONAL
b
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100
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PM
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c
[%] P=0.01
100
80
60
40
20
0
PM
CONVENTIONAL